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Simulation Analysis of Static Characteristics of CJX2-40 Type AC Contactor Electromagnetic Mechanism

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Abstract: At present, the finite element method has been widely used in electrical engineering; value has an absolute advantage in the field of solving the problem of position in the electromagnetic boundary. From the perspective of historical development, for solving the electromagnetic boundary value problems, four kinds of methods are used namely; graphical method, simulation method, analytical method and numerical calculation . This study introduced finite element method which has developed rapidly. Before finite element method, numerical calculation method was used, although this method was effective to a certain extent but the results showed that it had a limited range of the electromagnetic boundary value problems to be solved. .

Keywords: CJX2-40 type AC contactor, electromagnetic mechanism.

1. INTRODUCTION AND APPLICATION OF FINITE ELEMENT METHOD

Numerical calculation method used for solving electromagnetic boundary value problems includes four basic types of finite difference methods which include, , finite element method, integral equation method and boundary element method, and hybrid method, a method combining finite element method and boundary element method. Among them, finite element method is the major one [1].

The finite element method (FEM, Finite Element Method) which is also known as finite element or finite element method is based on the Galerkin or variation principle, was introduced in the twentieth century and has been used for 40 years; it has a profound background of engineering. It was initially introduced for mechanical calculation. Since then, it has been applied to calculate acceleration of the magnetic pole DC motor generating magnetic fields and for electromagnetic calculation. It is now used in the field of electrical engineering and has become significant for its widespread application. In the twentieth century, foreign aircraft manufacturing industry developed rapidly, with changes in the aircraft structure. However, accurate understanding of the static and dynamic characteristics of the aircraft is the most urgent, as the traditional design and methods for the analysis do not meet the requirements of the design; designs by engineers and the emergence of finite element method are effective [2]. The basic idea is to solve the discrete-made, the solution region is divided into a group of finite elements connected together in a certain way as to form a combined unit. This method is widely used to analyze heat conduction, fluid mechanics and electromagnetic field and continuity.

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Finite element method is an analysis method applied in many fields of engineering, especially numerical analysis method to approximate a solution for complex engineering problems. The basic concept is that the solution region, forming a complex continuous medium is divided into finite simple sub regions (unit), as equivalent domain of the original region, to solve the continuum variables (pressure, temperature, stress and displacement *etc*.); the problem is reduced to solving finite field variables on single element node value, and then the basic equation becomes an algebraic equation. This would solve the differential equations which are simplified into a set of algebraic equations, to obtain numerical solution [3-5].

The core of finite element method is the subdivision interpolation. It is a continuous process that divides the solution process into finite elements, and uses a simple interpolation function to represent each element of the solution, but it is not required for each unit test solution to satisfy the boundary conditions, but introduces boundary conditions for all the units after synthesis [6].

A mathematical model used to determine engineering or physics problems (the basic variables, the basic equations, solving domain and boundary conditions), was analyzed by the finite element calculation method and the main idea includes:

(1) The discrete-based of the continuum, namely element subdivision. Between the unit and the unit after discrete-based is only through node contact element nodes, set properties, such as the number, should be considered a problem, will directly affect the deformation form and calculation accuracy (generally, unit division and more detailed, more accurate description of the deformation, but the amount of calculation is larger). So the structure analysis in the finite element method is not the original object, discrete objects the same material but by many units linked together in a certain way, the obtained results for but approximate. (AUTHOR: Please clarify as it is too vague).

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(2) A mathematical model of the whole structure forms the characteristics of general linear equations to describe the unit. Node coordinates through the position space, with a certain degree of freedom (DOF) with mutual physical effect. Response characteristics of the degree of freedom can describe a physical field. The degree of freedom of finite element is analyzed by solving the node value. (AUTHOR: Please review).

(3) The use of electromagnetic theory and boundary conditions for each unit according to the original structure , gives equations of the finite element. [7].

(4) The unknown quantity to be solved for the unknown node.

2. THREE DIMENSIONAL STATIC MAGNETIC FIELD FINITE ELEMENT ANALYSIS

2.1. Appliance of Electromagnetic Field Theory

Maxwell laid the foundation of the classical theory of electromagnetic field. The electromagnetic field was proposed to describe the process of mathematics.Maxwell's equations and partial differential equations in the finite element method wereused to derive the equation using finite element method.

The integral form of the basic equations of electromagnetic is:

$$\oint_l H \cdot dl = i = \int_S \left(J + \frac{\partial D}{\partial t} \right) \cdot dS \tag{1}$$

$$\oint_l E \cdot dl = -\frac{\partial \varphi}{\partial t} = -\frac{\partial}{\partial} \int_S B \cdot dS \tag{2}$$

$$\oint_S D \cdot dS = q = \int_V \rho dV \tag{3}$$

$$\oint_S B \cdot dS = 0 \tag{4}$$

The relationship between various physical quantities of the electromagnetic field can be expressed by the electromagnetic auxiliary equation of isotropic constitutive relations for coal quality [8].

$$\left. \begin{aligned} D &= \varepsilon E \\ B &= \mu H \\ J &= \sigma E \end{aligned} \right\} \tag{5}$$

The coefficient is a constant for linear medium, but varies for nonlinear medium with the field strength. For any point in the research, field quantity relation must use the Maxwell equations in differential form. A vector field and its first order of spatial coordinates and partial time derivative may be in accordance with the Gauss theorem of vector analysis

$$\int_V divA\, dV = \oint_s A \cdot dS \tag{6}$$

And Stokes's theorem

$$\oint_l A \cdot dl = \int_S rotA \cdot dS \tag{7}$$

The Maxwell equations for differential forms

$$rotH = J + \frac{\partial D}{\partial t} \tag{8}$$

$$rotE = -\frac{\partial B}{\partial t} \tag{9}$$

$$divD = \rho \tag{10}$$

$$divB = 0 \tag{11}$$

These equations are suitable for various orthogonal coordinate systems. The electromagnetic fields in the electrical appliances based on orthogonal coordinate system involve rectangular coordinate and cylindrical coordinate. In vector analysis, the vector operator ∇ (called the Hamiltonian operator) and scalar operator Δ (called the Laplace operator), in a Cartesian coordinate system are expressed as

$$\nabla = \frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j + \frac{\partial}{\partial z} k \tag{12}$$

$$\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \tag{13}$$

Thus, field vector divergence, curl and so on appear on the Hamiltonian and the Laplasse operator as:

$$divA = \nabla \cdot A \tag{14}$$

$$rotA = \nabla \times A \tag{15}$$

$$divgrad\phi = \nabla \cdot \nabla \phi = \nabla^2 \phi = \Delta \phi \tag{16}$$

In the cylindrical coordinate, the relationship between the cylindrical coordinate r, θ, z and the Cartesian coordinate system x, y, z is that

$$x = \cos\theta \quad y = r\sin\theta \quad z = z \tag{17}$$

According to the above formula, the divergence and curl of the vector in cylindrical coordinates are expressed as:

$$divA = \frac{1}{r}\frac{\partial}{\partial r}(rA_r) + \frac{1}{r}\frac{\partial A_\theta}{\partial \theta} + \frac{\partial A_z}{\partial z} \tag{18}$$

$$\begin{aligned} rotA = &\left(\frac{1}{r}\frac{\partial A_z}{\partial \theta} - \frac{\partial A_\theta}{\partial z} \right) a_r + \left(\frac{\partial A_r}{\partial z} - \frac{\partial A_z}{\partial r} \right) a_\theta \\ &+ \frac{1}{r}\left[\frac{\partial}{\partial r}(rA_\theta) - \frac{\partial A_r}{\partial \theta} \right] a_z \end{aligned} \tag{19}$$

Electrical appliances in general have stable electric field and magnetic field; their field does not change with time. Maxwell equations are suitable for stable electric field, magnetic field, quasi stationary electromagnetic field and high frequency alternating electromagnetic field in different conditions.

2.2. The Electromagnetic Potential Equations

For the analysis and calculation of the problems related to electromagnetic field in electrical appliances and, for determining the relationship between the fields and the amount of field source, potential function as the auxiliary calculation method is used to simplify the problems. In the non-rotational field scalar potential function is used, while in the curl field vector potential function is used [9]. The Maxwell equation for constant current magnetic field is

$$\nabla \times v \nabla \times A = J \tag{20}$$

So for the nonlinear magnetic field, magnetic vector potential differential equation (20) is taken as the double curl equation. For the nonlinear ferromagnetic medium, magneto resistance ratio v not only determines function of the coordinates (x , y , z),but also the function of the magnetic induction with intensity A , which is the function of the magnetic vector potential. Static electromagnetic field boundary conditions include:

The first boundary condition

In the boundary of the magnetic vector, potential value is known.

The second boundary condition

Symmetry plane is taken as the second kind of boundary condition. In the boundary, tangential component of the magnetic field intensity is zero, which is the main problem in obtaining the double curl equation boundary value. In order to determine the relationship between the magnetic vector potential A and magnetic induction intensity B between single value, Coulomb gauge is introduced for steady magnetic field .

The double curl equation and the vector potential Poisson's equation, variation equation, through the principle of virtual work and the method of weighted residuals are discrete, finite element equation [10].

The double curl equation (20) of the residual equation can be written as,

$$\int_{\Omega} \left[W \cdot \left(\nabla \times v \nabla \times A \right) - W \cdot J \right] d\Omega = 0 \tag{21}$$

In the formula, W is Vector weighted function.

By the integral and Green transform, type (2-25) can be transformed into,

$$\int_{\Omega} \left[v \nabla \times W \cdot \nabla \times A - W \cdot J \right] d\Omega + \int_{\Gamma} W \cdot \left(n \times v \nabla \times A \right) d\Gamma = 0 \tag{22}$$

Consider the first boundary condition type (2-20) and the second boundary condition type (2-21), the weighted residual equation is simplified into

$$\int_{\Omega} \left[v \nabla \times W \cdot \nabla \times A - W \cdot J \right] d\Omega = 0 \tag{23}$$

Design

$$\hat{A} = \sum_{j=1}^{n} N_j A_j \tag{24}$$

A set of basic functions take the vector weighted function along with vector coordinate units, namely take [11],

$$W_i = N_i i, \left(i = 1,2,\cdots,n \right) \left(i = 1,2,\cdots,n \right) \tag{25}$$

The discrete type of, $\hat{A}$ and W_i (23) and (24), into type (25), is

$$\begin{aligned} \nabla \times \hat{A} = & \left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z} \right) i + \left(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x} \right) j \\ & + \left(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y} \right) k \end{aligned} \tag{26}$$

$$\nabla \times W_i = \frac{\partial N_i}{\partial z} j - \frac{\partial N_i}{\partial y} k \tag{27}$$

$$\begin{aligned} & \int_{\Omega} \begin{bmatrix} v \dfrac{\partial N_i}{\partial z} \left(\sum_j A_{xj} \dfrac{\partial N_j}{\partial z} - \sum_j A_{zj} \dfrac{\partial N_j}{\partial x} \right) - \\ v \dfrac{\partial N_i}{\partial y} \left(\sum_j A_{yj} \dfrac{\partial N_j}{\partial x} - \sum_j A_{xj} \dfrac{\partial N_j}{\partial y} \right) - N_i J_x \end{bmatrix} dxdydz \\ & = \sum_j A_{xj} v \int_{\Omega} \left(\frac{\partial N_i}{\partial z} \frac{\partial N_j}{\partial z} + \frac{\partial N_i}{\partial y} \frac{\partial N_j}{\partial y} \right) dxdydz + \\ & \sum_j A_{yj} v \int_{\Omega} \left(-\frac{\partial N_i}{\partial y} \frac{\partial N_j}{\partial x} \right) dxdydz + \sum_j A_{zj} v \int_{\Omega} \left(-\frac{\partial N_i}{\partial z} \frac{\partial N_j}{\partial z} \right) dxdydz \\ & - \int_{\Omega} N_i J_x dxdydz \\ & = 0 \end{aligned} \tag{28}$$

In the formula

$$C_{xx} = \int_{\Omega} \left(\frac{\partial N_i}{\partial y} \frac{\partial N_j}{\partial y} + \frac{\partial N_i}{\partial z} \frac{\partial N_j}{\partial z} \right) dxdydz$$

$$C_{xy} = -\int_{\Omega} \left(\frac{\partial N_i}{\partial y} \frac{\partial N_j}{\partial x} \right) dxdydz$$

$$C_{xz} = -\int_{\Omega} \left(\frac{\partial N_i}{\partial z} \frac{\partial N_j}{\partial x} \right) dxdydz$$

$$F_{xi} = \int_{\Omega} N_i J_x dxdydz$$

$$C_{xy} = -\int_{\Omega} \left(\frac{\partial N_i}{\partial y} \frac{\partial N_j}{\partial x} \right) dxdydz$$

$$C_{xz} = -\int_{\Omega}\left(\frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial x}\right)dxdydz$$

$$F_{xi} = \int_{\Omega} N_i J_x dxdydz$$

Similarly, take

$$W_i = N_i j\left(i = 1,2,\mathrm{L}\ \ ,n\right)\left(i = 1,2,\cdots,n\right) \tag{29}$$

than

$$\sum_j v\left(C_{yx}A_{xj} + C_{yy}A_{yj} + C_{yz}A_{zj}\right) = F_{yi}$$

$$\left(i = 1,2,\cdots,n\right) \tag{30}$$

In the formula,

$$C_{yx} = -\int_{\Omega}\left(\frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial y}\right)dxdydz$$

$$C_{yy} = \int_{\Omega}\left(\frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial x} + \frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z}\right)dxdydz$$

$$C_{yz} = -\int_{\Omega}\left(\frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial y}\right)dxdydz$$

$$F_{yi} = \int_{\Omega} N_i J_y dxdydz$$

Than take

$$W_i = N_i k,\left(i = 1,2,\cdots,n\right)\left(i = 1,2,\cdots,n\right) \tag{31}$$

is

$$\sum_j v\left(C_{zx}A_{xj} + C_{zy}A_{yj} + C_{zz}A_{zj}\right) = F_{zi} \bullet \left(i = 1,2,\cdots,n\right)$$
$$\left(i = 1,2,\cdots,n\right) \tag{32}$$

In the formula

$$C_{zx} = -\int_{\Omega}\left(\frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial z}\right)dxdydz$$

$$C_{zy} = -\int_{\Omega}\left(\frac{\partial N_i}{\partial y}\frac{\partial N_j}{\partial z}\right)dxdydz$$

$$C_{zz} = \int_{\Omega}\left(\frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial x} + \frac{\partial N_i}{\partial y}\frac{\partial N_j}{\partial y}\right)dxdydz$$

$$F_{zi} = \int_{\Omega} N_i J_z dxdydz$$

This can be a 3N order simultaneous equations.

The described equations wereobtained by vector method of weighted residuals obtained from the discrete equation and method according to the variable or virtual principle which worked exactly the same. Due to the use of vector weighted residual method, it was not needed to take into account functional variation. [16].

2.3. Finite Element Methods for Solving

1) The formation of nonlinear equations

All units in the solution area were added to the coefficient matrix and the right side of the matrix, to form the finite element equation

$$SA = F \tag{33}$$

The superposition coefficient matrix S neutron blocked S_{ij} composed of each unit body S_{ij}^e and became, (AUTHOR: Information missing. Please clarify) subscripts i, and j are the unit node numbers, i representing the sub array S_{ij}^e in throw, and j stands for S_{ij}^e in the S column. The sub array S_{ij}^e is of order 3×3 matrix [12].

$$S_{ij}^e = v_e C_{ij}^e = v_e\begin{bmatrix} C_{xx}^e & C_{xy}^e & C_{xz}^e \\ C_{yx}^e & C_{yy}^e & C_{yz}^e \\ C_{zx}^e & C_{zy}^e & C_{zz}^e \end{bmatrix} \tag{34}$$

These nine elements were addressed in the coefficient matrix of 3*i*-2、3*i*-1、3*i* respectively in the S line and 3*j*-2、3*j*-1、3*j* column.

Tetrahedral element with four nodes and 16 sub blocks S_{ij}^e, with each block having 9 elements, made atotal of 144 elements for each of the coefficient matrix. Three prism elements hadsix nodes, with a total of 324 elements for each of the coefficient matrix [13].

The right-hand matrix F neutron block F_i was composed of each unit body F_i^e superposed, and subscript i represented the sub array F_i^e in the line.

For a node i, the magnetic vector potential of the three component A_{xi}, A_{yi}, A_{zi}, in the array A, occupied 3*i*-2, 3*i*-1, and 3*i* number of rows respectively.

Geometrical dimension of coefficient matrix S was determined not only by the unit, but also by the function of unit reluctance v_e [14], suggesting that for the node of the magnetic vector potential function, the matrix equation (34) is nonlinear.

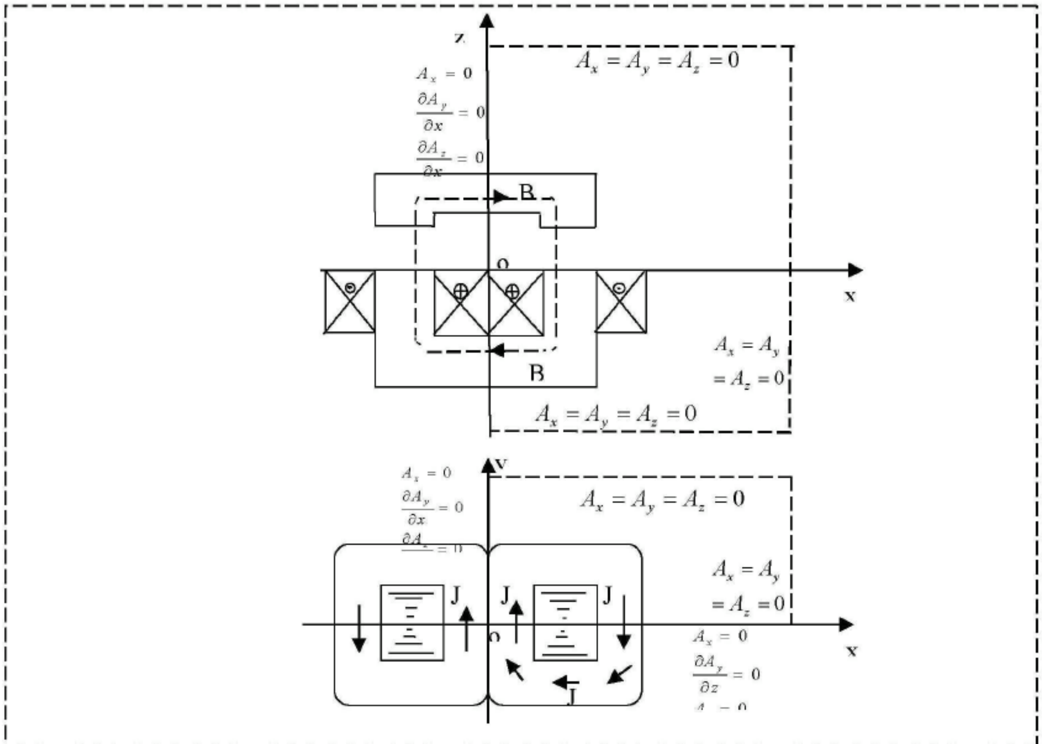

Fig. (1). The determination of boundary condition on U electromagnet.

Using the symmetry and sparsely of the coefficient matrix of the coefficient matrix using one-dimensional array contraction storage, one-dimensional array length. (AUTHOR: Please clarify)

Type $m(i)$ for the semi i bandwidth article for non zero blocked by 1, it wasequal to the maximum node and its adjacent node number difference. (AUTHOR: Please clarify)

2) Finite element method for solving

The nonlinear equation (34) can use Newton Raphael loose method; the iterative formula is:

$$A^{(q+1)} = A^{(q)} - \left[J^{(q)}\right]^{-1}\left[S^{(q)}A^{(q)} - F\right]$$

or

$$J^{(q)}A^{(q+1)} = F + \left(J^{(q)} - S^{(q)}\right)A^{(q)} \tag{35}$$

In the formula, for the number of iterations for superscript, Jacobi matrix is used.

First of all, the magnetic vector potential A has the initial value of zero, according to formula (35) iterative successive, (AUTHOR: The highlighted is vague. Please clarify)until it met the precision requirement.

Jacobi matrix J was obtained by the corresponding matrix J^e of each element from the collection:

$$J_{ij} = \sum_{e=1}^{e_0} J^e \tag{36}$$

Similarly, the Jacobi matrix J neutron block is also composed of each superposed unit J_{ij}^e.

$$J_{ij} = \sum_{e=1}^{e_0} J_{ij}^e \tag{37}$$

Unit matrix J_{ij}^e is

$$J_{ij}^e = \begin{bmatrix} J_{xx}^{ij} & J_{xy}^{ij} & J_{xz}^{ij} \\ J_{yx}^{ij} & J_{yy}^{ij} & J_{yz}^{ij} \\ J_{zx}^{ij} & J_{zy}^{ij} & J_{zz}^{ij} \end{bmatrix} = \begin{bmatrix} \frac{\partial f_{xi}}{\partial A_{xj}} & \frac{\partial f_{xi}}{\partial A_{yj}} & \frac{\partial f_{xi}}{\partial A_{zj}} \\ \frac{\partial f_{yi}}{\partial A_{xj}} & \frac{\partial f_{yi}}{\partial A_{yj}} & \frac{\partial f_{yi}}{\partial A_{zj}} \\ \frac{\partial f_{zi}}{\partial A_{xj}} & \frac{\partial f_{zi}}{\partial A_{zj}} & \frac{\partial f_{zi}}{\partial A_{zj}} \end{bmatrix} \tag{38}$$

In the formula

$$f_{xi} = v_e \sum_r \left(C_{xx}^{ir} A_{rx} + C_{xy}^{ir} A_{ry} + C_{xz}^{ir} A_{rz}\right)$$

$$f_{yi} = v_e \sum_r \left(C_{yx}^{ir} A_{rx} + C_{yy}^{ir} A_{ry} + C_{yz}^{ir} A_{rz}\right)$$

$$f_{zi} = v_e \sum_r \left(C_{zx}^{ir} A_{rx} + C_{zy}^{ir} A_{ry} + C_{zz}^{ir} A_{rz}\right)$$

i , j , r represent the numbering of the nodes, for four physical units i , j , $r = K$, M , N , L ; for the three prism unit i , j , $r = K$, M , N , K' , M' , N' This can be:

$$J_{uv}^{ij} = v_e C_{uv}^{ij} + \left(\frac{\partial v}{\partial B}\right)_e \frac{\partial B}{\partial A_{vj}} \left[\sum_r \left(C_{ux}^{ir} A_{xr} + C_{uy}^{ir} A_{yr} + C_{uz}^{ir} A_{zr}\right)\right]$$

$$= v_e C_{uv}^{ij} + \left(\frac{\partial v}{\partial B}\right)_e \sum_r \left(C_{ux}^{ir} A_{xr} + C_{uy}^{ir} A_{yr} + C_{uz}^{ir} A_{zr}\right) \times \tag{39}$$

$$\sum_r \left(C_{vx}^{ir} A_{xr} + C_{vy}^{ir} A_{yr} + C_{vz}^{ir} A_{zr}\right) \Big/ BV_e$$

3. SOLVING THE ELECTROMAGNETIC FIELD BOUNDARY CONDITIONS

In the calculation of the actual magnetic system, magnetic field boundary conditions were predominantly finite and symmetric. As shown in Fig (**1**), the following U type electromagnet was taken an example to illustrate the treatment of boundary conditions. Due to the symmetry of the magnetic system, only 1/4 space required calculation. The boundary conditions are as follows:

In the infinite magnetic induction intensity B=0, the magnetic vector potential A=0, and the node number of the boundary at the end, not included in the equations. (AUTHOR: The highlighted is vague. Please clarify).

In this kind of boundary, the strength H of the magnetic field is perpendicular to the boundary [15]. For example, for the U type electromagnet around both sides of the symmetric x=0 plane, the symmetry conditions for a uniform medium static magnetic field, and the relationship between the magnetic vector potential and current density can be expressed as symmetry conditions and to obtain the magnetic vector potential A , only x>0 of space requires calculation in the boundary (yoz on the plane).

This kind of boundary method is determined by the nodes according to the internal node number. For the boundary node i , A_{xi} was obtained according to the imposed boundary conditions, such as the diagonal elements of the coefficient matrix of row had great number (such as 10^{10}), and the right end zero item array line3i-2, satisfied the A_{xi} =0 condition. A_{yi} and A_{xi}, according to the natural boundary conditions, were regarded as internal node variables treated the same way as [16].

This kind of boundary magnetic field intensity vector was parallel to the boundary, and perpendicular to A, such as U type electromagnet plane xoz , according to the symmetry condition on the boundary.

This kind of boundary nodes is in accordance with the internal node number, for the boundary node i , A_{yi} and A_{xi}, according to variable processing imposed boundary conditions.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

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